Physiology & Behavior 151 (2015) 88–96

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/phb

Review

Effects of chewing on appetite, food intake and gut hormones: A systematic review and meta-analysis

Sophie Miquel-Kergoat [a,*], Veronique Azais-Braesco [b], Britt Burton-Freeman [c], Marion M. Hetherington [d]

[a] Wrigley (Mars Inc.), 1132 West Blackhawk Street, Chicago, IL 60642, USA
[b] VAB Nutrition, 1 Rue Claude Danziger, 63100 Clermont-Ferrand, France
[c] Nutrition Department, University of California, Davis, 3135 Meyer Hall, One Shields Avenue, Davis, CA 95616-5270, USA
[d] School of Psychology, University of Leeds, Leeds LS2 9JT, United Kingdom

HIGHLIGHTS

- Enhancing oral processing by prolonged chewing influences appetite and food intake.
- Meta-analysis revealed that chewing significantly reduced self-reported hunger.
- Systematic review revealed an effect of chewing on food intake.
- Increasing the number of chews per bite increased gut hormone release.
- Mastication promotes satiety by influencing appetite, intake and hormone release.

ARTICLE INFO

Article history:
Received 4 April 2015
Received in revised form 26 June 2015
Accepted 14 July 2015
Available online 15 July 2015

Keywords:
Chewing
Appetite
Food intake
Hunger
Gut hormones
Meta-analysis

ABSTRACT

Aim: To conduct a systematic review of the effects of chewing on appetite, food intake and gut hormones, and a meta-analysis of the effects of chewing on self-reported hunger.
Objectives: To seek insights into the relationship between chewing, appetite, food intake and gut hormones, and to consider potentially useful recommendations to promote benefits of chewing for weight management.
Materials and methods: Papers were obtained from two electronic databases (Medline and Cochrane), from searches of reference lists, and from raw data collected from the figures in the articles. A total of 15 papers were identified that detailed 17 trials. All 15 papers were included in the systematic review; however, a further five studies were excluded from the meta-analysis because appropriate information on hunger ratings was not available. The meta-analysis was conducted on a total of 10 papers that detailed 13 trials.
Results: Five of 16 experiments found a significant effect of chewing on satiation or satiety using self-report measures (visual analogue scales, VASs). Ten of 16 experiments found that chewing reduced food intake. Three of five studies showed that increasing the number of chews per bite increased relevant gut hormones and two linked this to subjective satiety. The meta-analysis found evidence of both publication bias and between study heterogeneity ($IA^2 = 93.4\%$, $tau^2 = 6.52$, $p < 0.001$) which decreased, but remained, when covariates were considered. Analysis of the heterogeneity found a substantial effect of the fasting period where the duration of fasting influenced the decrease in hunger due to chewing. Prolonged mastication significantly reduces self-reported hunger levels (hunger: −2.31 VAS point, 95% CI [−4.67, −1.38], $p < 0.001$).
Conclusions: Evidence currently suggests that chewing may decrease self-reported hunger and food intake, possibly through alterations in gut hormone responses related to satiety. Although preliminary, the results identify a need for additional research in the area. Focused, uniform, experimental designs are required to clearly understand the relationships that exist between mastication, appetite, satiety, food intake and, ultimately, body weight.

Contents

* Corresponding author at: Wrigley (Mars Inc.), 1132 West Blackhawk Street, Chicago, IL 60642, USA.
E-mail address: Sophie.Kergoat@Wrigley.com (S. Miquel-Kergoat).

http://dx.doi.org/10.1016/j.physbeh.2015.07.017

1. Introduction

Obesity is a serious problem worldwide. It is believed that the characteristics of contemporary societies promote or, at the very least, facilitate overconsumption [1]. This presents significant challenges to the majority of individuals who wish to maintain a healthy body weight.

Every day we make very simple choices such as deciding when, what and how much to eat [2]. Over our lifetime we combine these choices many thousands of times to achieve a number of goals such as to consume the optimum level and blend of essential nutrients and energy, to achieve optimum health, to socialize and to celebrate. However, energy intake must be balanced by expenditure while also meeting the physiological requirements of the body. When the intake of energy exceeds expenditure, an individual will gain weight. While the macrostructure of eating behavior may appear to involve simple choices, the mechanisms that underlie these choices are known to be complex [3,4].

Appetite is a term that is applied to a number of dimensions of eating behavior including preference, selection, and motivation to eat [5]. It can be considered as being the “desire for food” [6]. It is experienced as the sensation which motivates intake and can be present even in the absence of a physiological need. For example, the sight or smell of food can promote salivation and food intake. Conversely, satiation can be considered as the “process that leads to the termination of eating” [5]. Satiation controls meal size and is influenced by a number of feedback mechanisms, such as declining food preference (sensory specific satiety) and gastric fullness. Satiety is the “process in which further eating is inhibited” and occurs as a consequence of having eaten. The intensity of the satiety response is measured by the duration between meals and/or the amount of food consumed at the next meal [7]. Satiety is influenced by a number of pre-absorptive and post-absorptive feedback mechanisms. Together, satiation and satiety are integral processes controlling food intake and feeding behavior.

A key component of the environment that may affect food intake behavior is passive exposure to food stimuli. To date, most of the research published on the cognitive regulation of food intake has focused on conscious, deliberative mechanisms; however, environmental cues can also influence individuals beyond conscious awareness, and interact with complex control mechanisms that operate automatically. A growing body of evidence suggests that consumers perform poorly in estimating how much they have eaten and, as a consequence, are not accurate in adjusting their intake to match individual requirements.

Appetite, satiation and satiety are regulated by a number of internal factors that include chronobiology [8], the size and composition of the previous meal [9], an individual's activity level [10], and genotype [11]. Through repeated experience of these factors over time, appetite control becomes influenced by learning and expectations. The role of learning is important since this is a modifiable component in the control of eating and counters the idea that appetite is entirely determined by biological factors.

Evidence demonstrating the complex integration of internal and external cues that control eating behavior is growing [12–16]. Appetite, satiation and satiety are primed, in part, by cognitive and gastrointestinal processes even before food enters the mouth. Once food enters the mouth it is processed through mastication to increase its surface area to volume ratio to facilitate swallowing and aid indigestion efficiency. Chewing provides motor feedback to the brain related to mechanical effort reflecting food texture and it also exposes food particles to sensory receptors for the detection of flavor (taste and smell). While the chewing of food is an integral element of ingestion and digestion of food, it is unclear to what extent chewing and oro-sensory feedback influence satiation or satiety and impact on food intake. This possible effect of chewing on food intake could indeed be potentially relevant regarding the increasing burden of overweight and obesity worldwide.

Foods and beverages that can be consumed quickly are associated with overconsumption since the speed of eating bypasses the usual “oral metering” which is necessary for the full expression of satiation and satiety [17]. This is attributed to insufficient mastication and/or to reduced levels of oro-sensory signaling during eating, leading to limited cephalic-phase responses and delayed onset of satiety. Therefore, the aim of this study was to conduct a systematic review of the effects of chewing on appetite, food intake and gut hormones, and a meta-analysis of the effects of chewing on self-reported hunger. The hypothesis tested was that enhancing chewing during an eating occasion may also enhance satiation and satiety and reduce food intake. To address this aim, intervention trials meeting specific criteria were identified and reviewed and meta-analysis was performed. The objectives of the systematic review and meta-analysis were to seek insights into the relationship between mastication/chewing and food choice and intake, and to provide potentially useful recommendations to promote benefits of chewing for weight management.

2. Materials and methods

This section of the review follows guidelines detailed in the PRISMA Statement [18].

2.1. Literature search

This review analyzes original human clinical-trial results from studies investigating the effect of chewing or mastication on satiety and/or energy intake which have been published in English or French. Studies were identified by searching Medline (1985–February 2014) and Cochrane (no time limit) databases. Additional studies were identified by examining the reference lists of articles. The search terms used were [(mastication or chewing) and (satiety or appetite or “food intake” or “energy intake” or “food behaviour” or “food behavior” or “eating behaviour” or “eating behavior”)]. The search on Medline was limited to publications in which the target key words were present in the title or abstract. The search of Medline and Cochrane databases provided a total of 196 citations. 176 remained after any duplicates had been removed.

2.2. Study selection

Studies performed on sick or infirm participants, or on participants whose oral health or dentition was suspected to hamper normal chewing were excluded. Non-human studies or studies aiming to validate a device or method(s) were also excluded, as were studies in which the relationship between chewing and satiety or food intake was not assessed. Narrative reviews with no original data were not included.

Initial screening was performed on publication abstracts and final eligibility was assessed on the basis of the full text. Two reviewers among the authors independently assessed the pre-set criteria described above and disagreements were resolved by discussion between all authors. Data were extracted using a specially developed spreadsheet, pilot tested on a few studies which contained detailed and standardized information: (i) characteristics of participants (mean age, country of origin, BMI, dietary restriction); (ii) characteristics of the study, including its design, duration of the experiment, fasting period before the start of the experiment, what substance was used for mastication, and the duration from the start of the experiment to the lunch; (iii) primary outcome measure (e.g. change from baseline of VASs of hunger sensation for various conditions); and (iv)number of subjects for which study data were analyzed (i.e. sample size), mean effect and variability measures (SD or SEM).

Of the 176 citations, 141 were excluded in the initial screening step and 23 additional studies were excluded after in-depth reading. Major causes for exclusion were: failure to address the topic of this review, i.e. the effect of chewing (or mastication) on satiety and/or energy intake (81 articles failed these criteria) and non-eligibility of the population (64 articles excluded). Other reasons for exclusion were that studies were not on humans (three articles), were aiming at validating methods (8 articles) or were not written in English or in French (8 articles). The total is higher than 141 because several publications were excluded for multiple reasons. Twelve articles remained and three additional articles, complying with all eligibility criteria were identified from the reference list of examined publications. Thus, a total of 15 studies were eligible for inclusion in this review [19–33]. Two publications reported two independent studies [23,28]. Therefore 17 experiments were systematically reviewed (see Fig. 1).

For the purpose of the meta-analysis, five studies were excluded because appropriate information on hunger ratings was not available for inclusion in the analysis [26–29,31]. Ten studies were thus included, totaling 13 different experimental series because three publications reported data on sub-groups (obese vs lean subjects) [25], different types of foods [23], or different levels of gastric stimulation, performed simultaneously to chewing [30].

2.3. Characteristics of the included studies

All but two of the 17 trials were laboratory based [22,28] and all but one used within subjects designs (see Table 1). In these field-based studies food intake was measured by diet records and in the laboratory studies, food intake was weighed and converted into energy (kcal or kJ). Participants were mainly young adults (mean age varied from 20.3 to 31.1 years). Four studies (6 experiments) enrolled only male

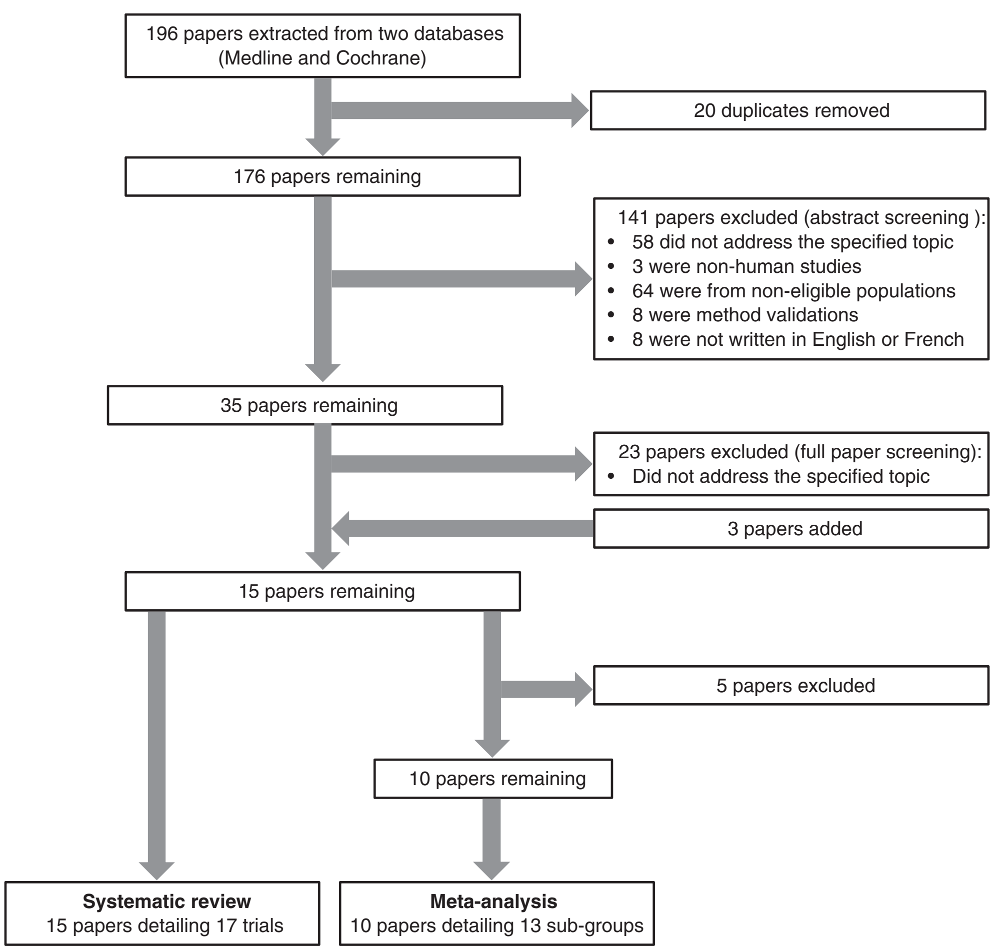

Fig. 1. Study selection process.

Table 1
Characteristics of the studies included in the systematic review of studies addressing the relationship between chewing and appetite, food intake and hormone levels in healthy human subjects (NA: not addressed; OB = obese; OW = overweight; HW = healthy weight). All studies are laboratory-based unless otherwise specified.

Reference	Participants		Intervention	Results		
	N	BMI	Design	Effect on appetite	Effect on energy intake	Hormones & metabolites
Cassady et al. [19]	13	HW	Fixed weight almonds (11 × 5-g portions) chewed 10, 25 or 40 times; within subjects	Yes, (40-chew condition differs from 25 chews, but not from 10-chews)	NA	No. But trend (p = 0055) for GLP-1 to be ↑ when chewing increases
Hetherington & Boyland [33]	60	HW	Fixed amount of gum chewed before access to ad libitum snack; within subjects	Yes, hunger ratings ↓ and fullness ratings ↑ in the gum condition	Yes, ↓ energy intake in gum condition	NA
Hetherington & Regan [20]	60	All (BMI from 19.6 to 37.3)	Fixed amount of gum chewed before access to ad libitum snack; within subjects	Yes, hunger and desire to eat ↓ and fullness ↑ in the gum conditions	Yes, ↓ energy from snack; no when considering energy of gum + snack	NA
Higgs & Jones [21]	43	HW	Fixed lunch normal chewing vs 10 s pause after each bite vs prolonged chewing Then ad libitum snack given 2 h later; between subjects	No effect on appetite ratings	Yes, ↓ energy intake in prolonged chewing condition	NA
Julis & Mattes [22]	50	OW or OB (BMIs 25–35)	Standard breakfast, standard lunch then 2 h later no gum, gum chewed for 20 min when hunger returns or chewed for 20 min followed by further 20 min delay; intake recorded at home by diet records; within subjects	No effect on appetite ratings	No effect on energy intake	NA
Laboure et al. (study A) [23]	12	HW	Fixed amount soup with different textures (puree or chunky mixture requiring no or longer chewing) then ad libitum buffet dinner; within subjects	No effect on appetite ratings	No effect on energy intake	↓ insulin after chewing; no effect on glucose & glucagon
Laboure et al. (study B) [23]	12	HW	Fixed bread rusk preloads with different textures (liquefied, dried or untoasted requiring no or longer chewing) given as lunch then ad libitum buffet dinner; within subjects	No effect on appetite ratings	No effect on energy intake	No difference in insulin. ↑ glucose after chewing
Lavin et al. [24]	20	HW	Fixed weight (150 g) of water, sucrose drink, sucrose jelly or sucrose pastilles (requiring no, some or long chewing) then ad libitum lunch; within subjects	No effect on appetite ratings	Yes, ↓ energy intake when food is chewed	NA
Li et al. [25] Study 1 (observational, not reported here) Study 2 (experimental)	30	16 HW 14 OB	Fixed amount of pork pie (300 g in 10-g pieces) chewed 15 or 40 times; 12 h later breakfast intake measured; within subjects	No effect on appetite ratings	Yes, ↓ energy intake when food is chewed longer	No effect on glucose or insulin Ghrelin ↓, GLP-1 ↑, CCK ↑ with more chews
Mattes & Considine [26]	60	HW and OB	Fixed period (15 min) of chewing (no gum, soft or hard gum) 4 h later ad libitum lunch; within subjects	No effect on appetite ratings	No significant effect [trend for lower intakes in HW and higher intakes in obese]	No effect on GLP-1 or ghrelin; glucose/insulin: ↓ below baseline later in PP period
Smit et al. [27]	11	6 HW and 5 OB	Ad libitum lunch — normal chewing, or chew each mouthful 15 or 40 times; within subjects	No effect on appetite ratings	Yes, ↓ energy intake when food is chewed longer	NA
Swoboda & Temple (study A) [28]	44	Moderately OW	No gum or fixed amount of gum (mint or fruit) chewed prior to a food reinforcement task; within subjects	Yes, hunger is ↓ in the gum conditions	Yes, ↓ energy intake from fruit in mint gum condition	NA
Swoboda & Temple (study B) [28]	54	Moderately OW	Field based — chew gum before all eating occasions for two weeks; intake measured by diary; within subjects	NA	No effect on energy intake, but fewer meals, more energy per meal and lower nutrient adequacy during gum weeks	NA
Weijzen et al. [29]	59		Ad libitum intake of chocolate and hazelnut cream filling biscuits given as "nibbles" (45 g) or as 16 g bars (more chewing with smaller bites); within subjects	No effect on appetite ratings	Yes, energy intake was when bite size was smaller	NA
Wijlens et al. [30]	26	HW	Fixed sham feed (1 min or 8 min) and simultaneous oral nasogastric administration of liquidized cake (100 ml or 800 ml) and control (no sham feed, nasogastric tube fitted but no liquid delivered); within subjects	No effect on appetite ratings	Yes; energy intake ↓ after 8 min sham feed vs 1 min sham feed	NA
Zhu et al. [32]	21	HW and OW	Fixed breakfast of pizza "bites" chewed 15 or 40 times; 3 h later ad libitum pasta intake recorded; within subjects	Yes; hunger, desire to eat and preoccupation with food were ↓ after longer chewing (no effect on fullness ratings)	No effect on energy intake	Yes more chews ↑ glucose, insulin and GIP and ↑ CCK; tend to ↓ decrease ghrelin
Zhu & Hollis [31]	45	HW, OW, and OB	Ad libitum pizza chewed 100%, 150% or 200% of normal number of chews; within subjects	No effect on appetite ratings	Yes;food intake ↓ when number of chews ↑ Yes: eating rate ↓ when number of chews ↑	NA

participants [23,25,30,32], 8 studies (9 experiments) broadly balanced gender ratios [19,22,24,26–28,31,33] and three studies enrolled more than 85% female participants [20,21,30]. Weight status varied across studies; in most studies, dietary restriction was an exclusion criterion and was assessed either using specific questionnaires or by asking whether the participants were on a slimming diet or wishing to lose weight. In only one study was "restrained eating" an inclusion criterion [20]. No study was truly blinded, as participants were entirely aware if they chewed or not; however, some protocols aimed at diverting the participant's attention from the real objective of the study [27,29,30]. Sample sizes ranged from 12 to 60 participants; sizes were based on power calculation in two studies only, with 21 participants needed to detect a 10% difference in subjective appetite or food intake [31] or 35 participants required to detect a 20% difference in energy intake, assuming a day to day variation of 27% [30]; in both cases, power was 0.8 with significance level of 0.05. Although most studies did not report power calculations, assessment of variance and effect size, suggests that many, but not all, had sufficient power in sample size to enable statistical significance to be observed.

Visual analogue scales (VASs) were used to rate various dimensions of appetite, including the minimum requirement selection criterion of hunger and level of fullness ratings.

All but one study used a within-subjects design, so that participants acted as their own controls. In the one exception [21] a standard lunch was given with instructions to chew normally or to pause for 10 s after each mouthful or to prolong chewing for 30 s. This study used a pause condition to match the extended time associated with prolonged chewing. Table 1 provides information on study design and the nature of the chewing manipulation. In some studies gum was chewed before meals or snacks [20,22,26,28,33]; in others a fixed amount of test food was given with texture manipulated [23,24,29] or with different instructions to chew [19,21,25,27,31,32]. As an example, two of these studies used fixed amounts of foods chewed at different rates [19,25] then participants were offered ad libitum food as a snack or meal. In another study, the food (cake) was sham-fed, thus it was chewed then expectorated [30] and at the same time food was delivered directly to the stomach to disassociate oral stimulation from gastric fill, and then food intake was recorded.

Five studies [19,23,25,26,32] included blood collection to assess changes in metabolic and gut hormone responses to mastication interventions that may be related to subject satiety responses or food intake outcomes. These studies used a multiple sampling paradigm collecting blood from subjects over 3–4 h every 15–30 min. Insulin and glucose were measured in all studies. Gut hormone evaluation included a combination of any three of the following: cholecystokinin (CCK), glucagon-like peptide-1 (GLP-1), glucose dependent insulinotropic peptide (GIP), ghrelin, polypeptide YY (PYY) and/or pancreatic polypeptide (PP).

2.4. Meta-analysis

A meta-analysis was conducted on the studies in which chewing was an experimental treatment and self-reported hunger was measured using 100 mm visual analogue scales (VASs). This analysis included, among the 15 studies identified for the systematic review, only those studies in which hunger was assessed and reported. When hunger was assessed at different time-points, the hunger ratings at 60 min (or the closest to 60 min) following the initiation of chewing were selected and retrieved (mean and SD) from the published tables or figures. In order to control for the large differences between studies in baseline values of reported hunger (which varied according to the time elapsed since last meal), the change in hunger rating (value 60 min after chewing minus baseline value) was used for analysis rather than the absolute VAS value for self-reported hunger.

A standard meta-analysis was performed using the R statistical software (version 3.0.2) and the metaphor package (version 1.9-4). The outcome measure was the mean difference in rated hunger between the conditions of prolonged mastication and normal/absent mastication. To investigate the degree of heterogeneity resulting from different experimental protocols and from the type and timing of the meal relative to the measured time-point, we used a random-effect model and DerSimonian–Laird estimates (1986) as our primary analysis. Inverse variance weighting was used for pooling. Between-study heterogeneity was quantified by calculating tau^2, IA^2 and HA2 statistics and by computing Cochran's Q test statistic. To investigate the risk of publication bias across studies, we produced funnel plots (SE of effect versus estimate of effect size for each study) and by computing the Kendall rank correlation test statistic (Kendall's tau) for the size of a standardized effect vs the SE values of the effect. The influence of each individual study on the overall results was analyzed by omitting one study at a time.

Heterogeneity was explored using a series of meta-regressions. The influence of each of the following characteristics was investigated: average age of the participants, year of the study, average BMI, fasting period (Fig. 2, period A) and duration between the time of the measure and the time of the meal (Fig. 2, period D).

3. Results

3.1. Effects of mastication on appetite

Of the 15 papers extracted by the review and 17 experiments presented in these papers the first positive study to reveal an effect of mastication on appetite is that by Cassady et al. [19]. In this study a fixed amount of almonds was chewed for a variable number of times. Thus 55 g of almonds (in 5 g portions) was chewed for a short (10), moderate (25) or large (40) number of times. Ratings were collected every 15 min after almond intake until 60 min and then taken again 90, 120 and 180 min (post-prandially). They found a significant effect of mastication on appetite ratings. Chewing the almonds 40 times produced the greatest suppression of hunger until 90 min and promoted fullness relative to baseline until 60 min. Chewing the almonds 25 times reduced hunger relative to baseline shortly after intake; however, later in the post-prandial period fullness was lower and hunger was higher in the 25 chew condition compared to baseline, 10 and 40 chews. While additional mastication through a systematic increase in chewing facilitated subjective satiety to the same energy load in the short term, a "dose–response" effect on appetite ratings was not observed. In fact, the moderate chewing condition (25 chews) produced a rebound hunger and fullness effect. Therefore, although effects on fat absorption in this study were dependent on particle size of the chewed almonds the appetite effect was not linear. In the first hour after chewing, appetite effects were greatest with the largest number of chews per portion but by the end of the experimental period, hunger and fullness returned to or were above baseline levels. The authors suggest that the moderate chewing (25 times) condition was the most familiar and comfortable; therefore, the 10 and 40 chew conditions might be considered extremes which are both unfamiliar and difficult to achieve [19].

Appetite suppression was also found in the studies on chewing gum by Hetherington and her colleagues [20,33] where participants chewed gum after lunch for 15 min each hour until a snack was provided 3 h later. In both cases chewing significantly increased fullness and reduced hunger, desire to eat, and desire to eat sweet snacks. An effect of chewing mint or fruit flavored gum for 10 min also had a significant suppressive effect on hunger relative to no gum according to Swoboda et al. [28] in their laboratory based experiment. However, no effect of chewing gum on appetite was found outside the laboratory according to Julis and Mattes [22]. In this field based study, participants were given a standard lunch in the lab then they followed one of the following conditions: no-gum, fixed time chewing gum or pre-meal chewing gum. In the fixed time condition, fruit-flavored gum was chewed 2 h after lunch for 20 min then when they wished to eat or drink they waited 20 min before eating ad libitum. For the pre-meal treatment there was no fixed interval until snacking, but when the desire to eat

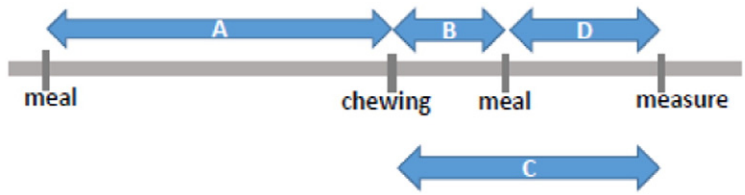

Fig. 2. Schematic view of the experimental protocols.

occurred they chewed gum for 20 min then consumed their food or beverage. Ratings were recorded electronically on a hand held personal digital assistant outside the laboratory. The lack of effect on hunger might be attributable to the relatively short chewing time; however, 10 min was sufficient to produce an effect on hunger in the lab-based study by Swoboda et al. [28]. Alternatively the lack of effect on hunger observed by Julis and Mattes [22] might be due to the greater variability associated with the naturalistic field setting compared to a laboratory setting.

In a laboratory based study comparing 15 versus 40 chews of pizza, greater masticatory effort produced a significant reduction in hunger, preoccupation with food and desire to eat [32]. In this experiment, 40 chews also produced significant effects on gut hormones (see below) but did not influence subsequent food intake. The authors suggest that chewing pizza 40 times may have influenced palatability and the effects on appetite may be secondary to this effect. They also propose that increasing chewing affects eating rate, particle size, bolus volume and processing time all of which may influence appetite. This study demonstrates both psychological and physiological effects of greater mastication on satiety. It is of course possible that there is reciprocal influence of these effects during the meal. Therefore, studies which manipulate the mastication component separately from the gastric component have aided our understanding of the effects of chewing on satiety such as that by Wijlens et al. [30]. These authors controlled simultaneously the oral and gastric effects on appetite by sham feeding a cake (chewed for 1 min or 8 min) and providing either a small (100 ml) or large (800 ml) infusion of liquidized cake directly into the gut. In all experimental conditions subjective hunger decreased and fullness increased relative to control but there was no differential effect of longer chewing on appetite in this experiment. However, the lack of differential effect between the two chewing conditions might be due to the relatively small difference in time between the two. From the previous studies which did find effects of chewing on appetite ratings the minimum chewing time was 10 min or 40 chews [20,28–31,34]. Therefore, it is reasonable to suppose that chewing effects are subject to a threshold either in terms of time or masticatory effort (Table 2).

3.2. Effects of mastication on food intake

The effect of mastication on food intake was stronger insofar as more trials found a significant effect of mastication on food intake. Overall 10 of 16 experiments which measured energy intake found a significant effect of chewing on ad libitum intake. The first to demonstrate this was Lavin et al. [24,33] who showed that sucrose containing preloads consisting of a chewable candy (pastilles) reduced energy intake at lunch compared to the same energy provided as a semi-solid (jelly) or as a drink. The pastilles took 10 min to chew, the jelly 5 min to eat and the drink 2 min to consume. Thus the conditions differed in both chewing effort and oral transit time. Nevertheless, despite showing no effect on appetite, participants reduced intake of a pasta and bread test meal following the pastilles compared to water and the sucrose drink preload. It can be concluded that prolonged chewing reduced intake at the lunch.

Five of the six studies showing a significant influence of mastication on intake found no effect on appetite ratings. For example, enhanced chewing of a lunch time meal [21] reduced intake of snack (candies) provided 2 h later, but had no effect on subjective appetite. This study controlled for the additional duration of the meal by including a condition with pauses between each mouthful. They found that participants enjoyed their meal less when asked to prolong chewing by 30 s for each mouthful and they reported that the vividness of the memory for the lunch meal was inversely related to how many candies were eaten. Chewing gum also reduced snack intake [20,33] and in one study reduced energy intake of healthy foods earned in a reinforcement trial [28].

When oral processing time is increased by prolonged chewing in a variety of studies [21,25,31] energy intake was reduced. When oral exposure was increased by reduced bite size [29] or by sham feeding [30] energy intake was also reduced. This latter finding was observed even when gastric input was minimal indicating the importance of the effect of oral exposure on satiation. Overall, these studies indicate that effortful chewing by providing chewing gum, or increasing the chewing effort or time can lead to reduced energy intake in some cases. However, in at

Table 2
Effect of chewing on hunger sensations and values of covariates for each study included in the meta-analysis. Fasting duration is defined as the time between the last meal and study initiation (Fig. 1, period A); time to lunch is the duration between chewing moment and first food ingestion (Fig. 1, period B); time of measure is the time between chewing and collection of VAS rating for hunger (Fig. 1, period C).

Study	Age		BMI		Sample size	Fasting duration (h)	Time to lunch (min)	Time to measure (min)	Hunger in LOW chewing group		Hunger in HIGH chewing group	
	Mean	SD	Mean	SD					Mean	SD	Mean	SD
Cassady et al. [19]	24.0	1.8	23.1	0.4	13	8	−120	60	−3.31	4.77	−9.8	2.2
Hetherington & Boyland [33]	21.7	4.0	22.7	3.4	60	4	60	60	−20.8	1.9	−24.7	1.7
Hetherington & Regan [20]	32.3	10.7	26.2	4.0	60	4	60	60	−46.3	2.5	−47.4	2.5
Higgs & Jones [21]	20.3	2.8	20.9	2.1	13	2	0	60	−55.7	17.3	−45.1	14.3
Li et al. [25] (study A)	20.8	0.8	20.1	2.0	16	12	30	60	−38.3	6.0	−43.6	5.3
Li et al. [25] (study B)	20.4	0.7	30.1	3.0	14	12	30	60	−37.1	7.8	−44.8	2.7
Zhu et al. [32]	24.0	1.0	24.8	0.6	21	12	60	60	−25.7	2.1	−30.6	6.1
Julis & Mattes [22]	24.0	1.0	28.3	0.4	47	3	0	60	2.0	1.0	2.0	1.0
Laboure et al. [23] (study A)	21.5	0.6	22.3	0.6	12	4	60	60	−59.7	7.0	−62.7	7.8
Laboure et al. [23] (study B)	21.5	0.6	22.3	0.6	12	4	60	60	−59.1	7.8	−61.5	7.8
Wijlens et al. [30] (study A)	21.0	2.0	22.0	3.0	26	3	15	60	−50.0	2.5	−48.0	2.5
Wijlens et al. [30] (study B)	21.0	2.0	22.0	3.0	26	3	15	60	−49.0	2.5	−48.5	2.5
Lavin et al. [24]	23.7	0.7	23.7	0.7	20	3	15	60	−53.9	8.4	−56.2	8.4

least one study this was specific to a reduced choice of healthy foods after the mint flavored gum [28], and this is important to consider when extrapolating beyond the laboratory based study, namely that reduction in intake may be selective for certain foods. What is not clear from the appetite or energy intake effects, is the potential mechanism of action. Therefore, in those studies which measured biomarkers, the potential mechanism of effect has been explored.

3.3. Effects of mastication on gut hormones

In the present review, 5 articles reported data on gut hormones or metabolic indices relative to chewing and satiety and/or food intake outcomes. Cassady et al. [19] provided a fixed amount of almonds (55 g in 5 g portions) to be chewed 10, 20 or 40 times. No differences among treatments were observed for glucose, PYY or ghrelin; however there was a trend ($p = 0.055$) for GLP-1 to be elevated after chewing almonds 40 times.

In a study providing a fixed amount of pizza in equal size portions [32], male participants ($n = 21$) chewed pizza either 15 or 40 times before swallowing. Compared to the 15 times, chewing 40 times before swallowing resulted in significantly elevated postprandial insulin, glucose, CCK and GIP and trends towards suppressed ghrelin. These results corresponded to enhanced satiety but not reduced food intake at subsequent meals. In contrast, Li et al. [25] found no effect of chewing cycles on subjective satiety, glucose or insulin, but did report increased CCK and GLP-1 and suppressed ghrelin after 40 vs 15 chews in a group of healthy weight and obese individuals. The effects were relatively consistent between healthy weight and obese sub-groups, although the satiety hormone responses were blunted in the obese compared to the healthy weight group. Two additional studies used texture modification paradigms to influence chewing effort [23,26]. Mattes and Considine [26] tested hard and soft chewing gums or no gum while sipping grape juice and showed no effect of chewing effort on satiety hormone responses. Likewise, no significant differences were observed on subjective satiety or food intake 4 h later, although a trend for decreased intake in healthy weight individuals and increased intake in obese individuals with chewing vs no chewing gum was observed. These responses are difficult to interpret with the available data, since authors described no other differential responses between healthy weight and obese individuals, including gastric emptying, gastro-intestinal transit or insulin and glucose responses. Laboure et al. [23] modified the textures of soup (puree vs chunky vegetable, bean and meat) or rusk (oven baked, liquefied, untoasted sandwich loaf). No satiety hormone responses were reported in this study; however, insulin and triglycerides were higher in the pureed soup option compared to chunky soup, a finding not repeated in the rusk meals despite textural differences.

3.4. Meta-analysis of the effect of chewing on self-reported hunger

The result of the primary meta-analysis in the random effect model showed a statistically significant effect of prolonged mastication on reducing hunger (hunger: −2.31 VAS point, 95% CI [−4.67, −1.38], $p = 0.0003$, Fig. 3). The effect estimate determined with the fixed effect model was −1.03, 95% CI [−1.37, −0.77], $p < 0.0001$.

Between studies heterogeneity ($IA^2 = 93.4\%$, $tau^2 = 6.52$) was statistically significant ($p < 0.0001$) as was expected. In documenting the potential for publication bias the funnel plot showed significant asymmetry (Fig. 4a).

Exploration of heterogeneity performed through meta-regressions provided evidence for a substantial effect of fasting period (Fig. 5), indicating that an increase in chewing effect on satiety was significantly related to increasing fasting time. This dependency further decreases the heterogeneity of the studies, which however still remained significant. The heterogeneity is reduced compared to the full model, but it is still significant as indicated by the homogeneity test: $Q_{(11)} = 163.9876$, $p < 0.0001$. Furthermore the funnel plot became symmetric (Fig. 4b). The influence of each individual series was analyzed by omitting one series at a time. One study [33] was found to be the biggest contributor to the heterogeneity. By removing this study the heterogeneity is reduced by 89.99%. The test for residual heterogeneity is still significant ($QE = 20.02$, $df = 10$, $p = 0.03$), possibly indicating that other moderators not considered in the model are influencing the effect of mastication.

4. Discussion

The aim of this study was to conduct a systematic review of the effects of chewing on appetite, food intake and gut hormone responses and further, to use a meta-analysis approach to evaluate the effects of chewing on self-reported hunger. The hypotheses tested were that enhancing chewing during an eating occasion would enhance satiation and satiety and reduce food intake. Overall, through the individual evaluation of experiments qualifying for this review, five of 16 [19,20,28,31,33] reported reduced hunger and appetite ratings with increased mastication or oral processing time. Eight of 16 studies [21,24,25,27,29,30,32,33] reported decreased energy intake with increasing mastication/oral processing, and a ninth study [26] showed trends for lower intake in healthy weight vs overweight subjects. Assessment of the mechanisms mediating satiety and/or appetite effects of mastication was included in five studies [19,23,25,26,32]. Of these, three studies [19,25,32] suggested that increasing the number of chews per bite increases (or suppresses) relevant gut hormones involved in satiety and food intake regulation.

Effortful mastication influenced subjective appetite in only one third of the studies identified by the systematic review. When suitable studies

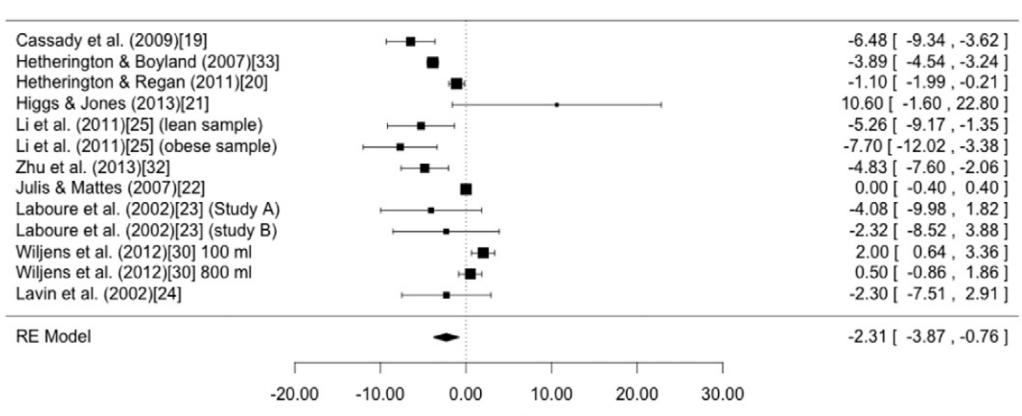

Fig. 3. Forest plot of effect of chewing on hunger sensation in a meta-analysis of 13 series.

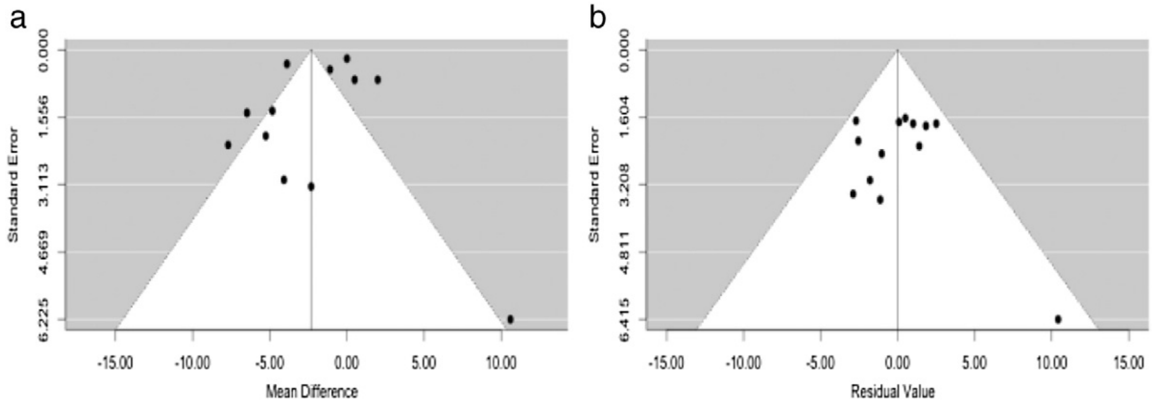

Fig. 4. Funnel plot used in assessing publication bias in the meta-analysis; a) without covariate analysis and b) using fasting period as a covariate.

were submitted to the meta-analysis despite evidence of publication bias, the effect of mastication on appetite was significant. In this qualitative analysis, only a minority of studies demonstrated a significant effect of chewing on satiation or satiety according to the subjective sensations measured by VASs. However, the design and outcome of the studies were variable and, when focusing on a subset of studies addressing similar endpoints in comparable designs, the trend appears to be in favor of suppressing hunger following increased chewing. This meta-analysis has a number of important limitations, including a strong publication bias and a significant heterogeneity which decreased, but remained, when covariates were considered.

However, this is to the best of our knowledge, the first meta-analytical approach assessing the relationship between chewing/mastication and hunger, and while preliminary, the results strongly support additional research in the area with focused, uniform experimental designs to clearly understand the mastication–satiety–food intake and ultimately body weight relationship. In particular, we found that the fasting time (i.e. the duration between the previous meal and the chewing time) is a strong determinant of heterogeneity; a better control of this parameter between studies could thus aid interpretation.

Effects of mastication on food intake were more clearly evidenced, since over half of the 16 eligible studies which measured subsequent food intake, showed a significant effect of chewing on intake. Prolonged chewing or increased oral exposure reduced food intake either at a later

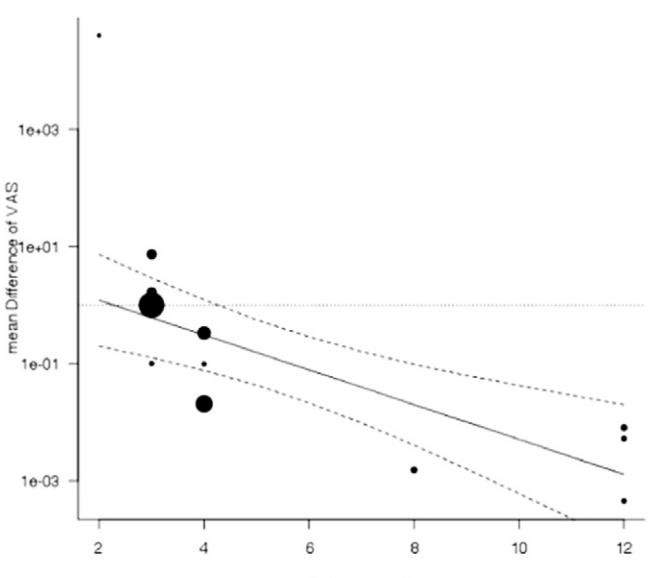

Fig. 5. Scatterplot representing the effect of fasting period (Fig. 1, period A) on the effect of chewing on self-reported hunger ratings.

meal or within the session. The common features of the studies which found a significant effect of chewing on satiety might relate to methodological rigor including the systematic way in which chewing was controlled. For example, when chewing gum reduced high energy snack intake [20,33] gum was chewed every hour on at least 3 occasions between the standard lunch and snack. However, when gum was chewed on only one occasion food intake was not affected [22,26] or intake of low energy density, healthy foods was reduced [28]. Even within the same laboratory there were inconsistent results which may be attributable to methodological differences, for example, comparing gum chewed in the laboratory with that at home [28] or comparing intake of prolonged chewing of a single food, namely pizza [32] with the effects of prolonged chewing of that food on later intake [31]. Overall, where gum was chewed more than once [20,33], where instructions extended normal chewing time [21,25,27,31], where different food forms involved prolonged chewing or bite size [24,29] or even when food was sham fed and chewed for longer [30] food intake was reduced.

Interestingly, subjective measures of satiety did not consistently match behavioral measures of satiety, i.e. ratings of appetite did not correspond with actual food intake. Thus in some of the studies even when no effect on appetite was observed, mastication did have a significant effect on intake. This variability between appetite ratings and how much is eaten has been reported previously [34]. While self-reported hunger, appetite and fullness ratings are taken as a proxy indicator of readiness to eat these ratings may not predict how much is eaten. Ratings of appetite may reflect motivation or drive to eat, but the amount of food actually eaten may be influenced by factors other than motivation such as expectancy, learning, habit or availability [1].

In any case, it is interesting to consider the impact of greater chewing effort and time on appetite and food intake since these could be exploited for appetite control if found to be reliable in other conditions. However, given the variability in findings across studies it is possible that any beneficial effects of chewing on appetite or intake are subject to a threshold either in terms of time or masticatory effort. In other words, it is important to identify the minimum chewing time or change in texture or form of the food required to produce a significant reduction in appetite or intake.

Overall, the available data are limited to make conclusions regarding the physiological underpinnings linking mastication, appetite control and food intake regulation. However, three of five studies addressing hormones in this systematic review suggested that increasing the number of chews per bite increases (or suppresses) relevant gut hormones involved in satiety and food intake regulation.

One of the first steps in ingesting food is to chew it to reduce particle size before swallowing. This chewing or act of mastication elicits an array of effects that impact digestive and absorptive processes, including physical signaling and chemical signaling that play important roles in appetite and food intake regulation. Among these effects is the increased bio-accessibility of nutrients for absorption and subsequent utilization impacting post-absorptive energy control mechanisms. Studies reporting increased blood glucose and insulin with increased chewing are likely explained by the greater accessibility of nutrients (e.g., carbohydrates) for absorption. The increased bioaccessibility imparted with chewing is also important for stimulation of pre-absorptive mechanisms, such as those involved in neuro-hormonal regulation of food intake, including CCK, GLP-1, PPY and ghrelin. Studies showing increased gut hormones (or suppressed ghrelin) and increased glucose and insulin with greater chewing would therefore be expected. The caveat is when food particle size is pre-manipulated, such as the case in the study by Laboure et al. [23], in which case the soup puree resulted in increased triglyceride and insulin response compared to the chewing condition. In other studies, disparity in responses may be explained by differences in nutrient composition of chewed foods (fat vs carbohydrate and total load). Interestingly, in the chewing gum study by Mattes and Considine [26], insulin and glucose declined with increasing chewing effort while sipping grape juice, with no apparent differences in other physical factors (e.g., gastric emptying). The effect was much later in the postprandial period, but nonetheless declines below baseline were evident suggesting a delayed effect of the chewing effort.

In addition to mastication effects on bio-accessibility of nutrients, mastication may also impact gut hormone release (or suppression) via activation of neural circuitry. Ghrelin, for example, is an appetitive hormone that is elevated in the blood in the fasting state and suppressed in response to food intake. Sham feeding models have shown that oral stimulation affects circulating ghrelin concentrations [35,36].

While few studies were available to be reviewed for understanding the physiological connection between enhanced satiety and mastication, 3 studies [19,25,32] indeed reported enhanced gut hormone responses and of those, two [19,32] also reported enhanced subjective satiety and the third reported reduced food intake at subsequent meal [25]. Future research to better understand the relationship between masticatory processing, food intake regulation and the underlying physiology could prove useful in developing dietary and/or behavioral strategies that can be adopted long-term to control food intake and achieve/maintain body weight goals.

In conclusion, evidence currently suggests that prolonged chewing reduces self-reported hunger in one third of eligible studies and reduced food intake in more than half of eligible studies. Meta-analysis confirmed the effect of chewing on self-reported hunger. Although preliminary, the results identify a need for additional research in the area. Focused, uniform, experimental designs are required to clearly understand the relationships that exist between mastication, satiety, food intake and, ultimately, body weight.

Conflicts of interest

VB has received fees from Wrigley for previous scientific consultancy activities.

Acknowledgments

The authors are grateful for the assistance of Mohamed Ben Haddou, CEO of MENTIS SA, 13 rue du Congrés, 1000 Bruxelles for his work on the meta-analysis and of Dr. Jon E. L. Day (Cerebrus Associates Limited, UK) in finalizing the manuscript for submission.

References

[1] M.M. Hetherington, Cues to overeat: psychological factors influencing overconsumption, Proc. Nutr. Soc. 66 (2007) 113–123.
[2] J.E. Day, I. Kyriazakis, P.J. Rogers, Food choice and intake: towards a unifying framework of learning and feeding motivation, Nutr. Res. Rev. 11 (1998) 25–43.
[3] H.R. Berthoud, The neurobiology of food intake in an obesogenic environment, Proc. Nutr. Soc. 71 (2012) 478–487.
[4] H.R. Berthoud, H. Munzberg, B.K. Richards, C.D. Morrison, Neural and metabolic regulation of macronutrient intake and selection, Proc. Nutr. Soc. 71 (2012) 390–400.
[5] J. Blundell, C. de Graaf, T. Hulshof, S. Jebb, B. Livingstone, A. Lluch, et al., Appetite control: methodological aspects of the evaluation of foods, Obesity Reviews: An Official Journal of the International Association for the Study of Obesity 11 (2010) 251–270.
[6] C. de Graaf, The validity of appetite ratings, Appetite 21 (1993) 156–160.
[7] J.E. Blundell, C.L. Lawton, J.R. Cotton, J.I. Macdiarmid, Control of human appetite: implications for the intake of dietary fat, Annu. Rev. Nutr. 16 (1996) 285–319.
[8] C. de Graaf, T. Hulshof, J.A. Weststrate, P. Jas, Short-term effects of different amounts of protein, fats, and carbohydrates on satiety, Am. J. Clin. Nutr. 55 (1992) 33–38.
[9] B.J. Rolls, V.A. Hammer, Fat, carbohydrate, and the regulation of energy intake, Am. J. Clin. Nutr. 62 (1995) 1086S–1095S.
[10] N.A. King, M. Hopkins, P. Caudwell, R.J. Stubbs, J.E. Blundell, Individual variability following 12 weeks of supervised exercise: identification and characterization of compensation for exercise-induced weight loss, International Journal of Obesity (2005) 32 (2008) 177–184.
[11] J. Cecil, M. Dalton, G. Finlayson, J. Blundell, M. Hetherington, C. Palmer, Obesity and eating behaviour in children and adolescents: contribution of common gene polymorphisms, International Review of Psychiatry (Abingdon, England) 24 (2012) 200–210.
[12] H.R. Berthoud, Multiple neural systems controlling food intake and body weight, Neurosci. Biobehav. Rev. 26 (2002) 393–428.
[13] H.R. Berthoud, Neural control of appetite: cross-talk between homeostatic and non-homeostatic systems, Appetite 43 (2004) 315–317.
[14] J.E. Blundell, Perspective on the central control of appetite, Obesity (Silver Spring, Md.) 14 (Suppl 4) (2006) 160S–163S.
[15] J. Schwartz, C. Byrd-Bredbenner, Portion distortion: typical portion sizes selected by young adults, J. Am. Diet. Assoc. 106 (2006) 1412–1418.
[16] J.R. Tregellas, K.P. Wylie, D.C. Rojas, J. Tanabe, J. Martin, E. Kronberg, et al., Altered default network activity in obesity, Obesity (Silver Spring, Md.) 19 (2011) 2316–2321.
[17] de Graaf, C. Why liquid energy results in overconsumption. Proc. Nutr. Soc. 2011,70: 162–70.
[18] A. Liberati, D.G. Altman, J. Tetzlaff, C. Mulrow, P.C. Gotzsche, J.P. Ioannidis, et al., The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration, BMJ (Clinical Research Ed.) 339 (2009) b2700.
[19] B.A. Cassady, J.H. Hollis, A.D. Fulford, R.V. Considine, R.D. Mattes, Mastication of almonds: effects of lipid bioaccessibility, appetite, and hormone response, Am. J. Clin. Nutr. 89 (2009) 794–800.
[20] M.M. Hetherington, M.F. Regan, Effects of chewing gum on short-term appetite regulation in moderately restrained eaters, Appetite 57 (2011) 475–482.
[21] S. Higgs, A. Jones, Prolonged chewing at lunch decreases later snack intake, Appetite 62 (2013) 91–95.
[22] R.A. Julis, R.D. Mattes, Influence of sweetened chewing gum on appetite, meal patterning and energy intake, Appetite 48 (2007) 167–175.
[23] H. Laboure, V. Van Wymelbeke, M. Fantino, S. Nicolaidis, Behavioral, plasma, and calorimetric changes related to food texture modification in men, Am. J. Physiol. Regul. Integr. Comp. Physiol. 282 (2002) R1501–R1511.
[24] J.H. Lavin, S.J. French, C.H. Ruxton, N.W. Read, An investigation of the role of oro-sensory stimulation in sugar satiety? International Journal of Obesity and Related Metabolic Disorders: Journal of the International Association for the Study of Obesity 26 (2002) 384–388.
[25] J. Li, N. Zhang, L. Hu, Z. Li, R. Li, C. Li, et al., Improvement in chewing activity reduces energy intake in one meal and modulates plasma gut hormone concentrations in obese and lean young Chinese men, Am. J. Clin. Nutr. 94 (2011) 709–716.
[26] R.D. Mattes, R.V. Considine, Oral processing effort, appetite and acute energy intake in lean and obese adults, Physiol. Behav. 120 (2013) 173–181.
[27] H.J. Smit, E.K. Kemsley, H.S. Tapp, C.J. Henry, Does prolonged chewing reduce food intake? Fletcherism revisited, Appetite 57 (2011) 295–298.
[28] C. Swoboda, J.L. Temple, Acute and chronic effects of gum chewing on food reinforcement and energy intake, Eat. Behav. 14 (2013) 149–156.
[29] P.L. Weijzen, D.G. Liem, E.H. Zandstra, C. de Graaf, Sensory specific satiety and intake: the difference between nibble- and bar-size snacks, Appetite 50 (2008) 435–442.
[30] A.G. Wijlens, A. Erkner, E. Alexander, M. Mars, P.A. Smeets, C. de Graaf, Effects of oral and gastric stimulation on appetite and energy intake, Obesity (Silver Spring, Md.) 20 (2012) 2226–2232.
[31] Y. Zhu, J.H. Hollis, Increasing the number of chews before swallowing reduces meal size in normal-weight, overweight, and obese adults, J. Acad. Nutr. Diet. 114 (2014) 926–931.
[32] Y. Zhu, W.H. Hsu, J.H. Hollis, Increasing the number of masticatory cycles is associated with reduced appetite and altered postprandial plasma concentrations of gut hormones, insulin and glucose, Br. J. Nutr. 1–7 (2012).
[33] M.M. Hetherington, E. Boyland, Short-term effects of chewing gum on snack intake and appetite, Appetite 48 (2007) 397–401.
[34] R. Mattes, Effects of aspartame and sucrose on hunger and energy intake in humans, Physiol. Behav. 47 (1990) 1037–1044.
[35] M. Arosio, C.L. Ronchi, P. Beck-Peccoz, C. Gebbia, C. Giavoli, V. Cappiello, et al., Effects of modified sham feeding on ghrelin levels in healthy human subjects, J. Clin. Endocrinol. Metab. 89 (2004) 5101–5104.
[36] H.P. Simonian, K.M. Kresge, G.H. Boden, H.P. Parkman, Differential effects of sham feeding and meal ingestion on ghrelin and pancreatic polypeptide levels: evidence for vagal efferent stimulation mediating ghrelin release, Neurogastroenterology and Motility: The Official Journal of the European Gastrointestinal Motility Society 17 (2005) 348–354.